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Impact of Air-side Economizer Control Considering Air Quality Index on Variable Air Volume System Performance

Sang-Hyeon Cho, Joon-Young Park, and Jae-Weon Jeong[†]

Department of Architectural Engineering, College of Engineeing, Hanyang Univeristy, Seoul 04763, Korea

Abstract

The objective of this study is to determine the effectiveness of a modified air-side economizer in improving indoor air quality (IAQ). An air-side economizer, which uses all outdoor air for cooling, affects the building's IAQ depending on the outside air quality and can significantly affect the occupants' health, leading to respiratory and heart disease. The Air Quality Index (AQI), developed by the US Environmental Protection Agency (US EPA), measures air contaminants that adversely affect human beings: PM10, PM2.5, SO2, NO2, O3, and CO. In this study, AQI is applied as a control for the operation of an air-side economizer. The simulation is analyzed, comparing the results between the differential enthalpy economizer and AQI–modified economizer. The results confirm that an AQI–modified economizer has a positive effect on IAQ. Compared to the operating differential enthalpy economizer, energy increase in an operating AQI–modified economizer is 0.65% in Shanghai and 0.8% in Seoul.

Keywords: Air-side economizer, AQI-modified economizer, Indoor air quality, Air quality index, $PM_{2.5}$

1. Introduction

Big cities in China generally exceed PRC pollution standards for 10% to 30% of the day (Chan and Yao, 2008), and 20.7% of China's cities exceed Grade II of the National Standard of China (Zhang and Rock, 2012). Globally, most big cities face air pollution problems, including Shanghai and Beijing in China and Seoul in South Korea. The poor air quality adversely affects human health, even indoors through HVAC systems. Schwartz and Dockery (1992) reported that each increase of 100 μg/m³ in total suspended particulates (TSP) increases mortality by 7%. Every 100 μg/m³ increase in TSP increases mortality by 10% among people over 65 and 3% among people under 65. In addition, a 10 μg/m³ increase in $PM_{2.5}$ increases mortality related to respiratory illness by 1.78%, related to stroke by 1.03%, and for all-cause mortality by 1.21% (Frankin et al., 2007). Linares and Diaz (2010) researched the relationship between $PM_{2.5}$ concentrations and hospital admissions using hospital data from 2003 to 2005 in Madrid, Spain. It shows that $PM_{2.5}$ concentration and hospital admissions have a linear relationship with no threshold. Every 10 μg/m³ increase in $PM_{2.5}$ raises mortality from diabetes mellitus by 11% (O'Donnell et al., 2011), significantly influences indoor allergens (Maesano et al., 2007), and reduces heart rate variability (Rodriguez et al., 2006). Pope et al. (2015) explained that people with asthma and fourth and fifth grade students experienced a decrease in pulmonary function of up to 6% compared to normal conditions when PM_{10} exceeded 150 μg/m³.

An air-side economizer, which uses only outdoor air for cooling, has the advantage of reducing the energy needed to run a HVAC system (Park et al., 2013). Aktacir (2012) researched monthly energy saving effect of air-side economizer in Antalya, Turky. In this energy simulation, three HVAC system operation, which are air-conditioning with no air-side economizer, differential enthalpy economizer and differential dry-bulb temperature economizer, are used to verify the energy consumption differences. The results showed the energy saving effects were the greatest in March and April. Specifically, 55% and 66% energy were saved in each operation of differential dry-bulb economizer and differential enthalpy economizer in March. 40% and 43% of energy were saved in each operation of differential dry-bulb economizer and differential enthalpy economizer in April. Yao and Wang (2010) analyzed differential dry-bulb temperature/enthalpy economizer effects in various climate zone of China. The selected regions are Shenyang, Beijing, Xian, Chengdu, Shanghai, Guangzhou. Operating differential dry-bulb saved more energy than operating differential enthalpy economizer in the northern region cities including Shenyang, Beijing and Xian. Otherwise in southern region cities, operating differential enthalpy economizer saved more energy. Comparing the two regions, operation in southern region cities saved more energy than operation in northern region cities due to the longer cooling period. LEE and Chen

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[†]Corresponding author: Jae-Weon Jeong
Tel: +82-2-2220-2370; Fax: +82-2-2220-1945
E-mail: jjwarc@hanyang.ac.kr

(2013) analyzed how differential enthalpy economizer affects energy saving in 17 different climate zone when indoor set temperature is 27ºC. In Climate zone 4A (mixed-humid) 33% of energy consumption decreased and in Climate zone 3C (warm-marine) 32% of energy consumption decreased. As indicated above, air-side economizer has an effect on saving the cooling energy in HVAC system.

However, outdoor air is not always clean so that operating an air-side economizer can cause problems because all the contaminants in the outdoor air enter the building space (Elkilani and Bouhamra, 2001). For this reason, the aim of this research is to suggest how to consider outdoor air quality in use of an air-side economizer.

1.1 Methodology

In this research, Air Quality Index (AQI) is introduced as a control to operate the air-side economizer. The AQI suggested by the US Environmental Protection Agency (US EPA) rates outdoor air pollution levels on a scale from 0 to 500, and will be described further in the next section. The suggested method is that the air-side economizer is stopped when the AQI exceeds 100, which is labeled "Unhealthy for sensitive groups." This methodology is depicted in Fig. 1, which describes conventional differential enthalpy economizer (DEE) and AQI-modified economizer (AME) operation algorithms. In Fig. 1(b), the added condition for activating the air-side economizer differs in two aspects between AME operation and DEE operation. One is that IAQ is improved by the air-side economizer ceasing to operate during times of bad air quality, even if the weather is suitable to operate the air-side economizer. The other is that chiller energy consumption increases compared to DEE because cooler outdoor air may not be able to be used; hence, the chiller must be operated to maintain a set indoor temperature.

To verify the effects of AME use, two simulations of DEE and AME operation were conducted. Indoor contaminant concentration was calculated by Eq. (1) in the simulation (Noh and Hwang, 2010). To confirm how energy consumption increases when operating an AME, an energy simulation including chiller, pump, and fan was also conducted for each case.

$$\begin{aligned} V\frac{dC_{in}}{dt} &= \{\varepsilon_{CCI}\cdot(C_{in}-C_{SA})+C_{SA}\}\cdot\{\varepsilon_{AEE}\cdot\dot{Q}_{SA}\cdot(1-\varepsilon_f)\} \\ &\quad +C_{OA}\cdot\dot{Q}_I\cdot P-C_{in}(\varepsilon_{AEE}\cdot\dot{Q}_{SA}+\dot{Q}_I+\dot{\beta}\cdot V)+\dot{S} \end{aligned} \tag{1}$$

where

V = volume of room (m^3)

C_{in} = indoor contaminant concentration (μg/m^3)

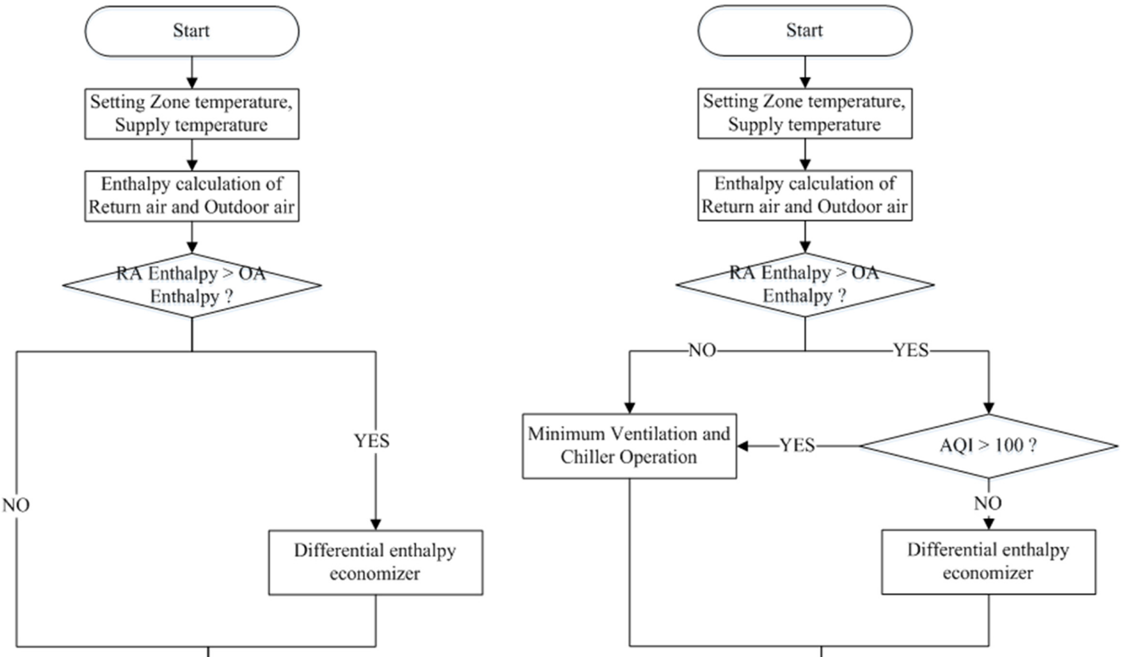
C_{SA} = contaminant concentration of supply air (μg/m^3)

C_{OA} = contaminant concentration of outdoor air (μg/m^3)

$\dot{Q}_{SA}$ = volume flow rates of supply air (m^3/min)

$\dot{Q}_I$ = volume flow rates of infiltration (m^3/min)

P = the penetration efficiency of particles through the air infiltration (-)



(a) Differential enthalpy economizer (b) AQI modified economizer

Figure 1. Air-side economizer algorithm.

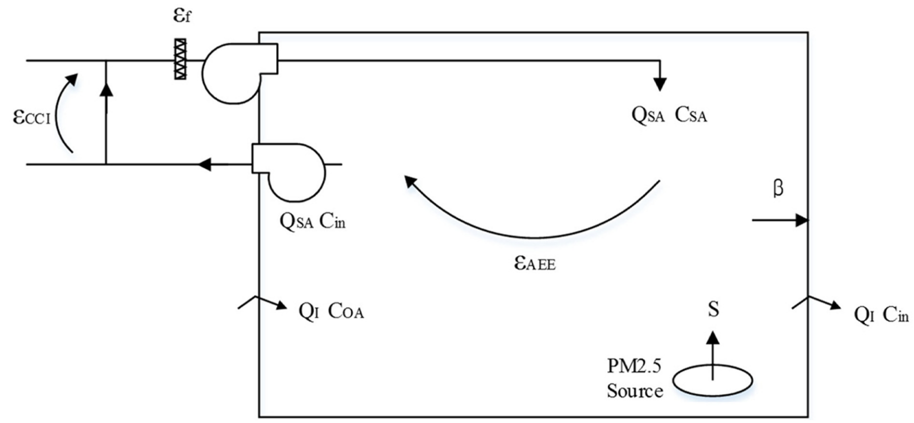


Figure 2. Mass balance model schematic.

ε_{CCI} = the cross contamination index around the exterior air vent (-)

ε_{AEE} = efficiency of air exchange effectiveness (-)

ε_f = filter efficiency (-)

S = emission rate of $PM_{2.5}$ in room ($\mu g/m^3$)

β = deposition rate of particles onto surfaces (h^{-1})

In simulating those cases, filters were also added. Filters states ranged from Minimum Efficiency Reporting Value (MERV) 8 to MERV 16, and the absence of a filter was also considered.

1.2. Air Quality Index

The AQI is calculated for six contaminants that adversely affect human health: $PM_{2.5}$, PM_{10}, ozone, carbon monoxide, nitrogen dioxide, and sulfur dioxide. Each AQI contaminant is calculated as in Eq. (2).

$$I_p=\frac{I_{Hi}-I_{Lo}}{BP_{Hi}-BP_{Lo}}(C_p-BP_{Lo})+I_{Lo} \quad (2)$$

where

I_p = the index for pollutant P (AQI_P)

C_p = the rounded concentration of pollutant P

BP_{Hi} = the breaking point that is greatest than or equal to C_p

BP_{Lo} = the breaking point that is less than or equal to C_p

I_{Hi} = the AQI value corresponding to BP_{Hi}

I_{Lo} = the AQI value corresponding to BP_{Lo}

In Eq. (2), the Guidelines for the Reporting of Daily Air Quality - the Air Quality Index (Park, 2006) regulates BP_{Hi}, BP_{Lo}, I_{Hi}, and I_{Lo}. The highest AQI calculated by each pollutant indicates air quality using the value scale presented in Table 1 (Park, 2006): From 0 to 50, air quality is "Good," from 51 to 100 air quality is "Moderate," from 101 to 150 air quality is "Unhealthy for Sensitive Groups," from 151 to 200 air quality is "Unhealthy," from 201 to 300 air quality is "Very Unhealthy," and above 301 air quality is "Hazardous."

Table 1. Breakpoints for the AQI

Breaking points							AQI	Category
O_3 (ppm) 8-h	O_3 (ppm) 1-h (1)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)	AQI	
0.000-0.064	-	0-54	0.0-15.4	0.0-4.4	0.000-0.034	(2)	0-50	Good
0.065-0.084	-	55-154	15.5-40.4	4.5-9.4	0.035-0.144	(2)	51-100	Moderate
0.085-0.104	0.125-0.164	155-254	40.5-65.4	9.5-12.4	0.145-0.224	(2)	101-150	Unhealthy for Sensitive Groups
0.105-0.124	0.165-0.204	255-354	65.5-150.4	12.5-15.4	0.255-0.304	(2)	151-200	Unhealthy
0.125-0.374	0.205-0.404	355-424	150.5-250.4	15.5-30.4	0.305-0.604	0.65-1.24	201-300	Very Unhealthy
(3)	0.405-0.504	425-504	250.5-350.4	30.5-40.4	0.605-0.804	1.25-1.64	301-400	Hazardous
(3)	0.505-0.604	505-604	350.5-500.4	40.5-50.4	0.805-1.004	1.65-2.04	401-500	

(1) Areas are required to report the AQI based on 8-h ozone values. However, in some areas, an AQI based on 1-h ozone values would be more protective. In those cases, the index for both the 8-h and the 1-h ozone values may be calculated and the maximum AQI reported.
(2) NO2 has no short-term NAAQS and can generate an AQI score only above values of 200.
(3) 8-h O_3 values do not define higher AQI values. AQI values of 301 or higher are calculated with 1-h O_3 concentrations.

2. Simulation

This simulation was conducted for office buildings in Seoul, Korea and Shanghai, China as both cities have high level of $PM_{2.5}$ concentration. $PM_{2.5}$ and AQI data were acquired from the Ministry of Environment of South Korea, which provides real-time air quality data, and from the Ministry of Environmental Protection of the People's Republic of China [18,19]. To perform the simulation, EnergyPlus, OpenStudio, and Excel were used. Minimum ventilation rate was set to 0.3 $L/s \cdot m^2$ for area and 2.5 L/s·person for people with an occupant density of 5 people/100 m^2 in an open office following the ASHRAE Standard 62.1 (2013). Table 2 describes details of the simulation conditions. The HVAC system was considered to be a VAV system, presented further as a schematic in Fig. 3.

Simulation assumptions were that the building has no infiltration of air and no $PM_{2.5}$ emission source, and that air exchange effectiveness ($\varepsilon_{A\varepsilon\varepsilon}$) is 100%. Cross contamination index around the exterior air vent (ε_{CCI}) is 0%, and deposition rate of particles onto surfaces (β) is 0. With these assumptions, the equation that solves for the indoor $PM_{2.5}$ concentration transforms into Eq. (3). Under those assumptions, the simulation was conducted per minute for one year.

IAQ is determined by various air contaminants; however, in this study, $PM_{2.5}$ concentration was used to determine IAQ level because $PM_{2.5}$ is the main factor of air pollution in Seoul and Shanghai and hard to be captured in a filter.

$$V\frac{dC_{in}}{dt} = \dot{Q}_{SA}\{(C_{SA})\cdot(1-\varepsilon_f)-C_{in}\} \tag{3}$$

Table 3 shows the effectiveness of capturing particles and pressure drop of each MERV rating. It is usually recommended to use MERV 8 for capturing pollutants in commercial buildings. However, MERV 8 has no capability of capturing $PM_{2.5}$. To complement MERV 8, another MERV ratings including from MERV 9 to MERV 16 were used in this simulation as well as MERV 8. $PM_{2.5}$ ranges from 1.0 to 3.0 micrometer (E2). Applied filtering efficiency is zero in MERV 8; 25% in MERV 9; 50% in MERV 10; 65% in MERV 11; 80% in MERV 12; 90% in MERV 13, MERV 14, and MERV 15; and 95% in MERV 16.

The filter is more effective with higher filter rating so that more $PM_{2.5}$ is going to be filtered with higher filter rating. In this research, however, it's not the issue to verify the capability of filter rating itself. It is focused that how the indoor air quality will be improved depending on the two different air-side economizers operation, AME and DEE, with same filter in each rating. Further, applied pressure drop is 150 Pa in MERV 8, 250 Pa in MERV 9 to 12, 350 Pa in MERV 13 to 16 in fan energy simulation.

Table 2. Building conditions for simulation

Building information	Building type		Office building
	Location		Shanghai/Seoul
	Volume		10 m * 10 m * 3 m (D * W * H)
	Area		100 m^2
	Floor		1
	Window-Wall ratio		0.5
	Temperature setting		24°C
	U-Value	External wall	0.59 $W/m^2 \cdot K$
		Roof	0.27 $W/m^2 \cdot K$
		Floor	0.50 $W/m^2 \cdot K$
		Window	2.27 $W/m^2 \cdot K$
HVAC system	VAV system		
	Air-side economizer type		DEE, AME
	Filter		Not installed / MERV 8-16
	Fan efficiency		0.5
	Pump efficiency		0.6
Office hours	AM 9:00 - PM 6:00		

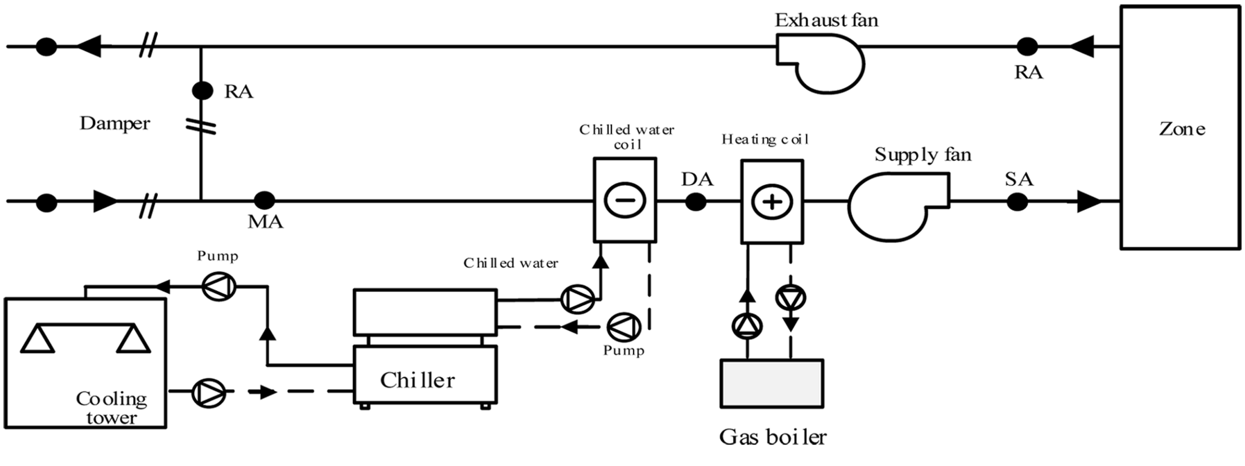


Figure 3. Schematic of VAV system.

Table 3. MERV Parameters with Minimum Final Resistance (ASHRAE Standard 52.2)

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency (%) in Diameter Range (μm)			Minimum Final Resistance	
	0.30-1.0 (E1)	1.0-3.0 (E2)	3.0-10.0 (E3)	Pa	in. of water
1	NA	NA	E3<20	75	0.3
2	NA	NA	E3<20	75	0.3
3	NA	NA	E3<20	75	0.3
4	NA	NA	E3<20	75	0.3
5	NA	NA	20≤E3<35	150	0.6
6	NA	NA	35≤E3<50	150	0.6
7	NA	NA	50≤E3<70	150	0.6
8	NA	NA	70≤E3	150	0.6
9	NA	E2<50	85≤E3	250	1.0
10	NA	50≤E2<65	85≤E3	250	1.0
11	NA	65≤E2<80	90≤E3	250	1.0
12	NA	80≤E2	90≤E3	250	1.0
13	E1<75	90≤E2	90≤E3	350	1.4
14	75≤E1<85	90≤E2	90≤E3	350	1.4
15	85≤E1<95	90≤E2	90≤E3	350	1.4
16	95≤E1	95≤E2	95≤E3	350	1.4

3. Results

The simulation results were analyzed through indoor $PM_{2.5}$ accumulation, annual $PM_{2.5}$ average concentration and total number of minutes exceeding $PM_{2.5}$ threshold. Also, the energy simulation of HVAC system operating AME and DEE was progressed by OpenStudio, EnergyPlus and Excel.

DEE operation time was calculated by EnergyPlus and it was integrated with provided AQI data of Shanghai and Seoul for calculating AME operation time. This air-side economizer operation time affects the indoor $PM_{2.5}$ state and HVAC energy consumption calculation of next iteration because it decides outdoor air ratio for air-conditioning.

3.1. Indoor $PM_{2.5}$ Accumulation

In Seoul, over a simulated trial period of one year, the DEE's operating time was 129,926 min (about 2,165 h) and the AME's operating time was 103,641 min (about 1,727 h). In Shanghai, the DEE's operating time was 67,929 min (about 1,132 h) and AME's operating time was 46,286 min (about 771 h) because AME operation stopped if the AQI exceeded 100. Considering this operating time decrease, outdoor air quality is poor with increased time of AQI exceeding 100. It can harm human health unless air-side economizer is controlled with outdoor air

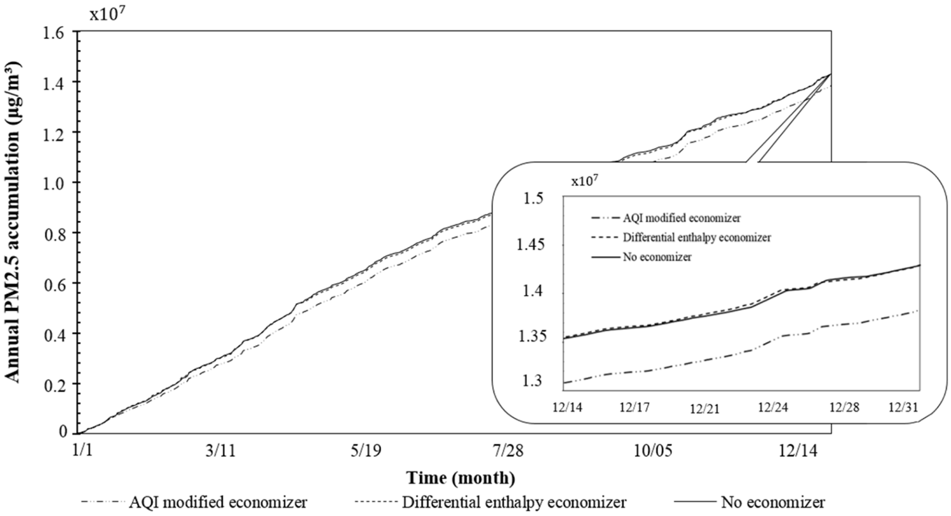


Figure 4. Annual $PM_{2.5}$ accumulation curve of Seoul.

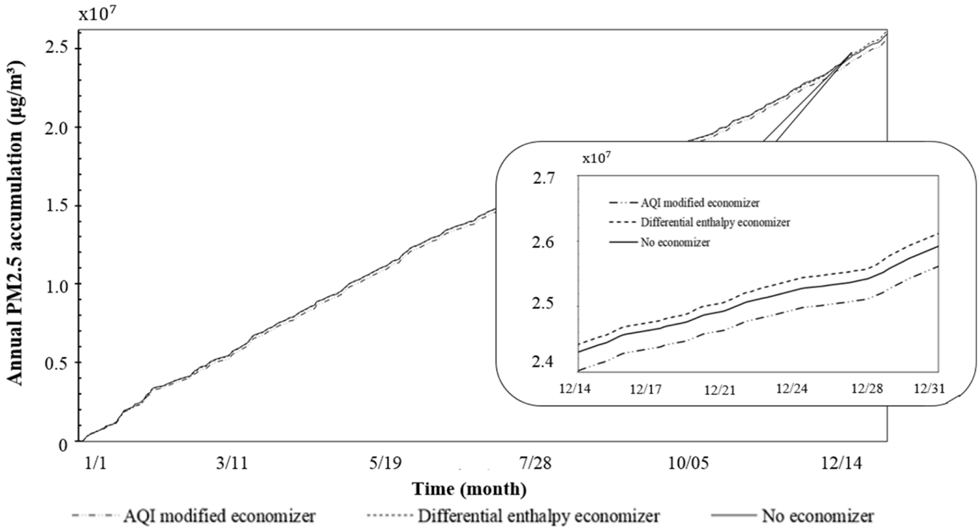


Figure 5. Annual $PM_{2.5}$ accumulation curve of Shanghai.

quality. Therefore, outdoor air quality should also be considered in drawing conclusions regarding the air-side economizer's operation.

Figs. 4 and 5 indicate the annual indoor $PM_{2.5}$ accumulation with no economizer, and using DEE and AME without filters in Seoul and Shanghai, respectively. AME operation shows that $PM_{2.5}$ accumulation decreased by 3.19% (from 14,294,261 μg/m^3 to 13,837,611 μg/m^3) in Seoul and 1.92% (from 26,114,723 μg/m^3 to 25,612,055 μg/m^3) in Shanghai compared to DEE operation.

Use of a DEE resulted in worse indoor air quality than use of an AME because DEE operation allow that all outdoor air comes into the space whether the outdoor air quality is good or not. However, an AME considers the quality of outdoor air in order to reduce appropriately the annual indoor $PM_{2.5}$ accumulation.

3.2. Analysis depending on MERV grade

This section describes the analysis of indoor concentration of $PM_{2.5}$ comparing AME and DEE operation with different filter ratings, from MERV 8 to MERV 16. There were two analyses; one that compared the annual average $PM_{2.5}$ concentration between AME and DEE operation and the other that compared how long $PM_{2.5}$ levels exceeded different standards during AME and DEE operation.

3.2.1. Seoul

As shown in Fig. 6, when comparing AME to DEE operation in Seoul, the annual average indoor concentration of $PM_{2.5}$ decreased from 27.20 μg/m^3 to 26.33 μg/m^3

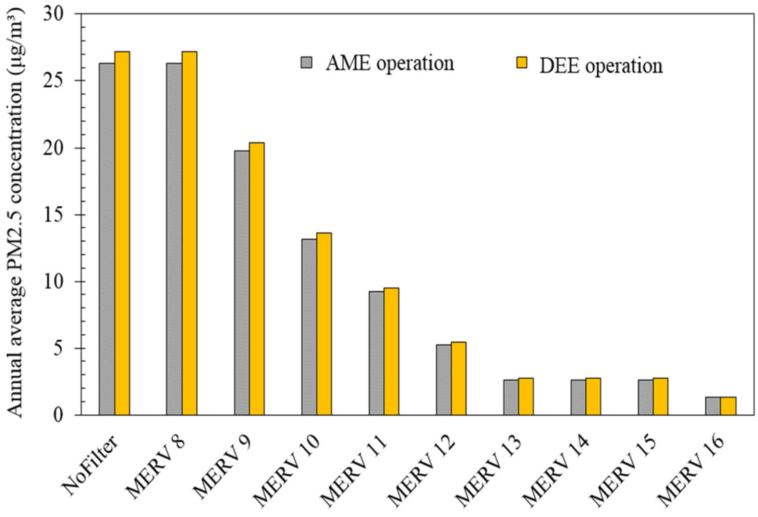


Figure 6. Annual average $PM_{2.5}$ concentration by MERV grade, Seoul.

for both no filter and MERV 8, from 20.40 μg/m³ to 19.75 μg/m³ with MERV 9, from 13.60 μg/m³ to 13.16 μg/m³ with MERV 10, from 9.52 μg/m³ to 9.21 μg/m³ with MERV 11 and from 5.44 μg/m³ to 5.27 μg/m³ with MERV 12. MERV 13 to MERV 16 have similar effects on both DEE and AME operation.

Fig. 7 shows the length of time that $PM_{2.5}$ exceeded the limit allowed by two standards. This graph compares the South Korean standard from an enforcement ordinance in a framework act on environmental policy (average $PM_{2.5}$ in 24 h, 50 μg/m³) and the WHO international standard (average $PM_{2.5}$ in 24 h, 25 μg/m³).

Based on the South Korean standard, when comparing AME and DEE operation, the total number of minutes for which $PM_{2.5}$ levels exceeded the allowable threshold fell from min (about 857 h) to 50,019 min (about 833 h) with no filter and MERV 8, respectively. Higher rated filters reduced time from 25,915 min (about 432 h) to 22,420 min (about 374 h) with MERV 9, from 3,063 min (about 51 h) to 931 min (about 16 h) with MERV 10, and from 22 min to 0 min with MERV 11. MERV 12 to MERV 16 do not allow $PM_{2.5}$ concentrations to exceed allowable amounts during both DEE and AME operation.

Based on the WHO standard, when comparing DEE and AME operation, the total number of minutes exceeding $PM_{2.5}$ threshold fell from 227,264 min (about 3788 h) to 224,861 min (about 3747 h) with no filter and MERV 8, respectively. Higher rated filters reduced time from 130,839 min (about 2181 h) to 124,209 min (about 2070 h) with MERV 9, from 51,434 min (about 857 h) to 42,819 min (about 714 h) with MERV 10, from 16,452 min (about 274 h) to 12,155 min (about 202 h) with MERV 11, and from 129 min (about 2 h) to 0 min with MERV 12. MERV 13 to MERV 16 do not allow $PM_{2.5}$ levels to exceed allowable amounts during both DEE and AME operation.

3.2.2 Shanghai

As shown in Fig. 8, when comparing use of DEE and AME, the annual average indoor concentration of $PM_{2.5}$ in Shanghai decreased from 49.69 μg/m³ to 48.73 μg/m³ with no filter and MERV 8, respectively. Higher rated filters reduced contamination from 37.26 μg/m³ to 36.55 μg/m³ with MERV 9, from 24.84 μg/m³ to 24.36 μg/m³ with MERV 10, from 17.39 μg/m³ to 17.06 μg/m³ with MERV 11, from 9.94 μg/m³ to 9.75 μg/m³ with MERV 12, from 4.97 μg/m³ to 4.87 μg/m³ with MERV 13 to MERV 15, and from 2.48 μg/m³ to 2.44 μg/m³ with MERV 16.

Fig. 9 shows the length of time that $PM_{2.5}$ exceeded the limit allowed by two standards. This graph compares the Chinese standard published by the Ministry of Environmental Protection of the People's Republic of China (average $PM_{2.5}$ in 24 h, 75 μg/m³) and the WHO international standard (average $PM_{2.5}$ in 24 h, 25 μg/m³).

Based on the Chinese standard, when comparing use of DEE to AME, the total number of minutes exceeding $PM_{2.5}$ threshold fell from 92,586 min (about 1,543 h) to 86,828 min (about 1,447 h) with no filter and MERV 8 operated, respectively. Higher rated filters reduced time from 34,048 min (about 567 h) to 28,666 min (about 478 h) with MERV 9, from 6,947 min (about 116 h) to 6,057 min (about 101 h) with MERV 10, and from 1658 min (about 28 h) to 534 min (about 9 h) with MERV 11. MERV 12 to MERV 16 do not allow $PM_{2.5}$ concentrations to exceed the threshold.

Based on the WHO standard, when comparing use of DEE to AME, the total number of minutes exceeding $PM_{2.5}$ threshold fell from 426,229 min (about 7,104 h) to 425,917 min (about 7,099 h) with no filter and MERV 8, respectively. Higher rated filters reduced time from 338,751

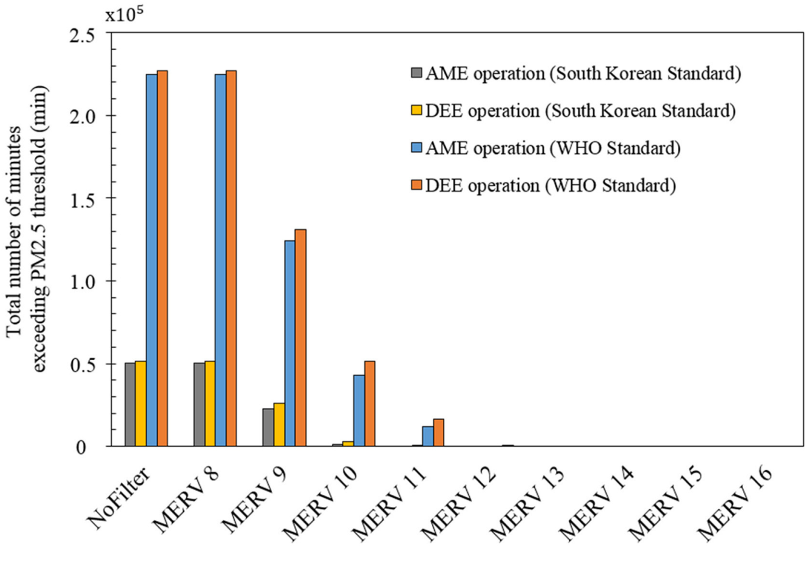


Figure 7. The total number of minutes exceeding $PM_{2.5}$ threshold, Seoul (WHO standard, South Korean standard).

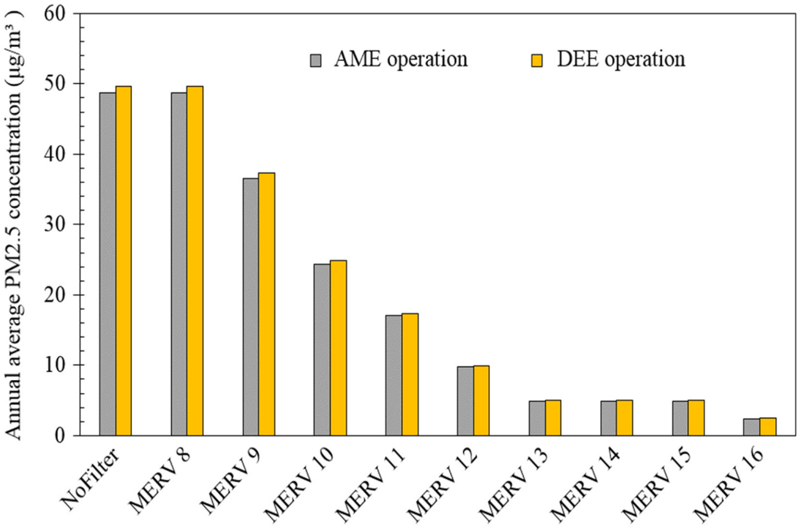


Figure 8. Annual average $PM_{2.5}$ concentration by MERV grade, Shanghai.

min (about 5,646 h) to 336,658 min (about 5,611 h) with MERV 9, from 194,856 min (about 3,248 h) to 188,867 min (about 3,148 h) with MERV 10, from 104,261 min (about 1,738 h) to 97,102 min (about 1,618 h) with MERV 11, from 15,694 min (about 262 h) to 16,078 min (about 268 h) with MERV 12, from 661 min (about 11 h) to 18 min with MERV 13 to MERV 15. MERV 16 does not allow $PM_{2.5}$ concentrations to exceed the threshold.

3.3 HVAC energy analysis

Table 4 describes the fan, chiller, and pump electric energy consumption for different MERV ranges in Seoul and Shanghai. Energy consumption in Seoul and Shanghai increased as MERV grade increased because pressure drop additionally increased by 150 Pa in MERV 8, 250 Pa for MERV 9 to MERV 12 and 350 Pa for MERV 13 to 16. For chiller, energy consumption in both cities shows an increase when AME is used, compared with DEE at the same MERV grade. This is because AME monitors the outdoor air quality to operate the air-side economizer, so free cooling time is reduced as compared to DEE, and the chiller operates with minimum ventilation rate when air-side economizer stops owing to bad air quality. When AME operates in the same MERV grade, pump energy use also increases as chiller energy use increases since pump operation is required when chiller is in operation.

4. Discussion

This paper analyzed the air-side economizer considering

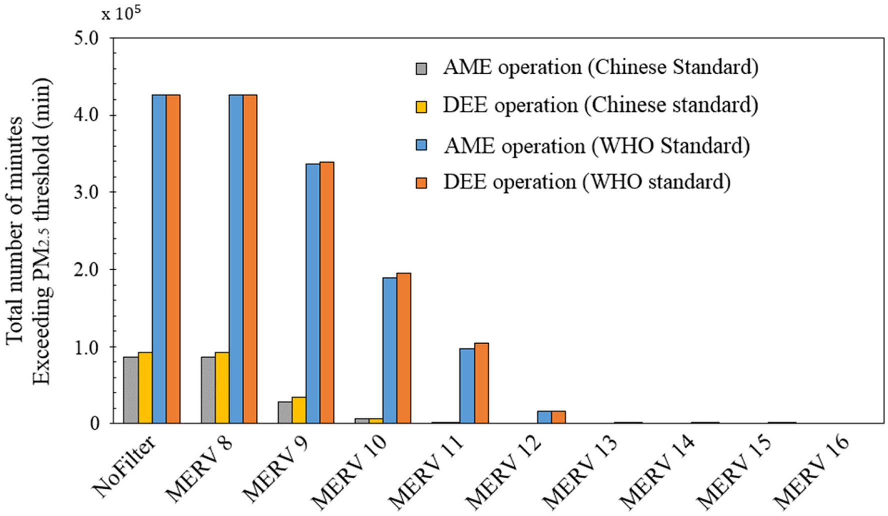


Figure 9. The total number of minutes exceeding $PM_{2.5}$ threshold, Shanghai (WHO standard, Chinese standard).

Table 4. HVAC energy consumption of AME and DEE operation

Seoul		No Filter	MERV 8	MERV 9-12	MERV 13-16
AME	Fan [kWh]	477.16	620.23	715.65	811.09
	Chiller [kWh]	2310.18	2332.45	2347.49	2362.62
	Pump [kWh]	1332.14	1346.27	1355.22	1364.86
DEE	Fan [kWh]	477.17	620.24	715.66	811.10
	Chiller [kWh]	2290.23	2312.17	2326.98	2341.89
	Pump [kWh]	1318.84	1332.63	1341.38	1350.83
Shanghai		No Filter	MERV 8	MERV 9-12	MERV 13-16
AME	Fan [kWh]	516.63	662.72	764.68	866.68
	Chiller [kWh]	3756.01	3651.63	3670.55	3689.61
	Pump [kWh]	1612.34	1618.91	1630.69	1642.85
DEE	Fan [kWh]	516.63	662.72	764.69	866.69
	Chiller [kWh]	3736.59	3632.97	3651.61	3670.40
	Pump [kWh]	1592.90	1598.80	1610.34	1621.88

the effect that AQI has on IAQ and HVAC energy consumption in Seoul, Korea and Shanghai, China. Table 5 shows that annual average $PM_{2.5}$ concentration decreased by about 3.2% in Seoul and about 1.9% in Shanghai during all AME operation with all filter ratings. By contrast, in each filter condition of AME operation, HVAC energy use increased by 0.8% in Seoul and 0.65% in Shanghai compared with use of a DEE.

It has been confirmed through the results of the simulation that use of an AME has a greater positive impact on the air quality than simple operation of an air-side economizer. At the same time, the increase in HVAC energy consumption, especially in chiller, was relatively low. The use of AME decreases possible free cooling time so that the chiller operates longer; however, simulations show little difference in HVAC energy consumption between AME and DEE operation for a year. Therefore, the suggested air-side economizer control, AME, is the better method to maintain IAQ than a conventional air-side economizer.

The annual total number of minutes exceeding $PM_{2.5}$ threshold in Seoul and Shanghai are described in Table 6 and Table 7, respectively, for both AME and DEE operation. The decrease in total number of minutes exceeding $PM_{2.5}$ threshold differs distinctly between AME and DEE at same MERV rating.

AME has an effect on reducing the time exceeding threshold under the South Korea standard as the MERV rating is getting low in Seoul. However, there are no $PM_{2.5}$ reducing effect through AME operation when filter rate is over than MERV 11. AME makes the IAQ improvements generally under the WHO standard in Seoul. However, AME operation do not make meaningful results of reducing $PM_{2.5}$ concentration over than MERV 12. This is because filtering efficiency is so high that filter can capture a lot of $PM_{2.5}$ without AME control. In Shanghai, AME operation also shows that $PM_{2.5}$ concentration get reduced under the Chinese standard and WHO standard. However, over than MERV 12, there are no IAQ improvements via AME operation by the same reason.

Therefore, we found out that AME brings positive effect under relatively the lower rating MERV than higher one.

Table 5. Comparison of annual average $PM_{2.5}$ concentration and HVAC energy consumption both AME and DEE

		No Filter	MERV 8	MERV 9	MERV 10	MERV 11	MERV 12	MERV 13-15	MERV 16
Annual average $PM_{2.5}$ concentration ($\mu g/m^3$), Seoul	AME	26.33	26.33	19.75	13.16	9.21	5.27	2.63	1.32
	DEE	27.20	27.20	20.40	13.60	9.52	5.44	2.72	1.36
$PM_{2.5}$ reduction ratio, Seoul		3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%
Annual average $PM_{2.5}$ concentration ($\mu g/m^3$), Shanghai	AME	48.73	48.73	36.55	24.36	17.06	9.75	4.87	2.44
	DEE	49.69	49.69	37.26	24.84	17.39	9.93	4.97	2.48
$PM_{2.5}$ reduction ratio, Shanghai		1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%
Electricity demand (kWh), Seoul	AME	4,119.5	4,299.0	4,418.4	4,418.4	4,418.4	4,418.4	4,538.6	4,538.6
	DEE	4,086.2	4,265.0	4,384.0	4,384.0	4,384.0	4,384.0	4,503.8	4,503.8
Rate of energy increase, Seoul		0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
Electricity demand (kWh), Shanghai	AME	5,885.0	5,933.3	6,065.9	6,065.9	6,065.9	6,065.9	6,199.1	6,199.1
	DEE	5,848.1	5,894.5	6,026.7	6,020.7	6,020.7	6,026.7	6,159.0	6,159.0
Rate of energy increase, Shanghai		0.65%	0.65%	0.65%	0.65%	0.65%	0.65%	0.65%	0.65%

Table 6. Reduction in time of exceeding $PM_{2.5}$ standard threshold in Seoul

Unit (min)		No filter & MERV 8	MERV 9	MERV 10	MERV 11	MERV 12	MERV 13-16
South Korean Standard	AME	42,819	22,420	931	0	0	0
	DEE	51,434	25,915	3,063	22	0	0
Time reduction		8,615	3,495	2,132	22	0	0
WHO Standard	AME	224,861	124,209	42,819	12,155	0	0
	DEE	227,264	130,839	51,434	16,452	129	0
Time reduction		2,403	6,630	8,615	4,297	129	0

Table 7. Reduction in time of exceeding $PM_{2.5}$ standard threshold in Shanghai

Unit (min)		No filter & MERV 8	MERV 9	MERV 10	MERV 11	MERV 12	MERV 13-15	MERV 16
Chinese Standard	AME	87,076	28,666	6,057	534	0	0	0
	DEE	90,495	34,048	6,947	1,658	0	0	0
Time reduction		3,419	5,382	890	1124	0	0	0
WHO Standard	AME	425,917	336,658	188,867	97,102	16,078	18	0
	DEE	426,229	338,751	194,856	104,261	15,694	661	0
Time reduction		312	2,093	5,989	7,159	-384	643	0

It can be applied with commercial building commonly used MERV 8 or MERV 9.

The exceeding time increased slightly according to the simulation results of MERV 12 by WHO standard in Table 7. It is considered that the air-side economizer operation stopped as AQI exceeded 100 because of other pollutants not $PM_{2.5}$. In this research, the air-side economizer operation stops to prevent the increase of indoor ozone amount when AQI exceed 100 due to ozone. There are high concentration of ozone, low concentration of $PM_{2.5}$ as described in Table 8. On the contrary, indoor $PM_{2.5}$ concentration will increase when air-side economizer stops operating because indoor air has higher $PM_{2.5}$ concentration than outdoor air. Therefore, little time of exceeding $PM_{2.5}$ standard threshold recommended by WHO increases.

Even though $PM_{2.5}$ concentration slightly increase in MERV 12 by WHO standard in Shanghai, overall indoor $PM_{2.5}$ concentration decreased in Seoul and Shanghai via AME without related MERV rating because the main reason of air pollution in both cities is $PM_{2.5}$.

5. Conclusion

As outdoor air is contaminated by $PM_{2.5}$, PM_{10}, ozone, carbon monoxide, nitrogen dioxide, and sulfur dioxide, as in recent years, increasing numbers of people suffer from illnesses like respiratory and heart disease. To improve IAQ, AQI is applied to an air-side economizer as a control that monitors the outdoor air quality state automatically during air-side economizer operation. Research findings are as follows when operating AME rather than DEE. It reduces the annual $PM_{2.5}$ accumulation, the annual average $PM_{2.5}$ concentration and decreases the total number of minutes exceeding $PM_{2.5}$ threshold both local and WHO standards.

Table 8. Other pollutants causing AQI exceeding 100 in Shanghai (Ministry of Environmental Protection of the People's Republic of China)

Time	$AQI_{PM2.5}$	AQI_{PM10}	AQI_{O3}	AQI_{SO2}	AQI_{NO2}	AQI_{CO}	AQI	Main Pollutant
2015-04-23	87	69	113	22	89	20	113	O_3
2015-04-24	85	79	49	23	108	23	108	NO_2
2015-04-26	74	65	140	19	55	15	140	O_3
2015-04-28	97	71	112	20	50	25	112	O_3
2015-05-13	62	72	127	23	70	18	127	O_3
…	…	…	…	…	…	…	…	…
2015-09-04	94	66	155	15	29	25	155	O_3
2015-09-11	39	46	104	15	49	15	104	O_3
2015-10-03	54	59	114	13	40	18	114	O_3
2015-11-12	78	61	21	15	102	25	102	NO_2
2015-11-28	92	73	26	21	112	28	112	NO_2

MERV 12 to 16 are so efficient that we found no difference in $PM_{2.5}$ concentration during AME operation. However, under the MERV 11, AME operation improves indoor air environments as blocking air pollutants.

In considering HVAC energy consumption, AME use consumed more electricity overall, particularly in chiller, but there was little impact to total annual energy consumption. Therefore, AME use can achieve a good indoor air environment for occupants' health with a small increase in energy consumption in commercial buildings.

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References

Aktacir. M.A. (2012). "Performance Evaluation of Different Air-side Economizer Control Method for Energy Efficient Building." Journal of Thermal Science and Techology. 32:2, 19-30.

ANSI/ASHRAE Standard 52.2. (2012) Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size. American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. Atlanta, GA.

ANSI/ASHRAE Standard 62.1. (2013) Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. Atlanta, GA.

Chan, C.K. and Yao, X. (2008). "Air Pollution in Mega Cities in China." Atmospheric Environment. 42, 1-42.

Elkilani, A. and Bouhamra, W. (2001). "Estimation of Optimum Requirements for Indoor Air Quality and Energy Consumption in Some Residences in Kuwait." Environmental International. 27, 443-447.

Frankin, M., Zeka, A., and Schwartz, J. (2007). "Association between $PM_{2.5}$ and All-Cause and Specific-Cause Mortality in 27 US Communities." Journal of Exposure Science and Environmental Epidemiology. 17, 279-287.

Lee, K.P. and Chen, H.L. (2013). "Analysis of Energy Saving Potential of Air-side Free Cooling for Data Centers in Worldwide Climate Zones." Energy and Buildings. 64, 103-112.

Linares, C. and Diaz, J. (2010). "Short-term Effect of $PM_{2.5}$ on Daily Hospital Admissions in Madrid (2003-2005)." Environmental of Health Research. 20:2, 129-140.

Maesano, I.A., Moreau, D., Caillaud, D., Lavaud, F., Moullec, Y.L., Taytard, A., Pauli, G., and Charpin, D. (2007). "Residential Proximity Fine Particles Related to Allergic Sensitisation and Asthma in Primary School Children. Respiratory Medicine. 101, 1721-1729.

Noh, K.C. and Hwang, J.H. (2010). "The Effect of Ventilation Rate and Filter Performance on Indoor Particle Concentration and Fan Power Consumption in a Residential Housing Unit." Indoor and Built Environment. 00:0, 1-9.

O'Donnell, M.J., Fang, J., Mittleman, M.A., Kapral, M.K., and Wellenius, G.A. (2011). "Fine Particulate Air Pollution ($PM_{2.5}$) and the Risk of Acute Ischemic Stroke." Epidemiology. 22:3, 422-431.

Park, S.H., Seo, J.H., Jung, Y.H., Chang, H.J., and Hwang, S.H. (2013). "Energy Consumption Analysis based on Filter Differential Pressure when Adopting an Air-Side Economizer System for a Data Center." Korean Journal of Air-Conditioning and Refrigeration Engineering. 25:7, 371-376.

Park, T. (2006) Guideline for Reporting of Daily Air Quality - Air Quality Index (AQI). U.S. Environmental Protection Agency. No.EPA-454/B-06-001 14.

Pope, C.A. (2015). "Ischaemic Heart Disease and Fine Particulate Air Pollution." Heart. 101, 248-249.

Pope, C.A., Dockery, D.W., Spengler, J.D., and Raizenne, M.E. (1991). "Respiratory Health and PM_{10} Pollution." American Review of Respiratory Disease. 144, 668-674.

Riojas, H. Escamilla, J.A., Gonzalez, J.A., Tellez, M.M., Vallejo, M., Santos, C., and Rojas, L. (2006). "Personal $PM_{2.5}$ and CO Exposures and Heart Rate Variability in Subjects with Known Ischemic Heart Disease in Mexico City." Exposure Science and Environmental Epidemiology, 16, 131-137.

Schwartz, J. and Dockery, D.W. (1992). "Increased Mortality in Philadelphia Associated with Daily Air Pollution Concentrations." American Review of Respiratory Disease. 145, 600-604.

WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide, Global update 2005, Summary of risk assessment. (2005). World Health Organization.

Yao, Y. and Wang, L. (2010). "Energy Analysis on VAV System with Different Air-side Economizer in China." Energy and Buildings. 42:8, 1220-1230.

Zhang, C. and Rock, B. (2012). "The Prospect for Using Air-side Economizers in China." Proc. International Conference on Sustainable Design and Construction, Kansas City, Missouri, USA, March 23-25.